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A visual basic application for Microsoft® Excel 2007 has been developed as a helpful tool to perform mass, energy, exergy and thermoeconomic (MHBT) calculations during the systematic analysis of energy processes simulated with Aspen Plus®. The application reads an Excel workbook containing three sheets with the matter, work and heat streams results of an Aspen Plus® simulation. The required information from the Aspen Plus® simulation and the algorithm/calculations of the application are described and applied to an Air Separation Unit (ASU). This application helps the designer when MHBT analyses are performed, as it increases the knowledge of the process simulated with Aspen Plus®. It's a valuable tool not only because of the calculations performed, but also because it creates a new Excel workbook where the results and the formulae written on the cells are fully visible and editable. There is free access to the application and it has no protection allowing changes and improvements to be done.

1. Introduction

Project engineers need tools to study different alternatives of energy processes to improve them. Instead of an optimisation (understood as a continuous offer of alternatives), engineers compare a discrete number of different options [2] selecting the most appropriate for the process considering all the external and internal constraints involved in the project. Due to the difficulties concerning process improvement or optimisation, engineers need flexible, intuitive and powerful tools to reduce the time consumed in monotonous calculations in order to increase the time used for the evaluation of the results and comparison of the alternatives.

Probably the success of the Aspen Plus® simulation software, among other software, is the ability to "build" and compare easily and quickly different alternatives showing the user the matter and energy results of the alternatives proposed.

A Microsoft® Excel VBA tool has been developed to help the engineer when performing exergy and thermoeconomic analyses of processes that have been simulated using Aspen Plus®. The application is needed because Aspen Plus® does not have an integrated function to calculate the exergy of the streams presented in a process, nor to evaluate thermoeconomic costs, although it gives enough thermodynamic data and can also estimate capital costs. In order to calculate the exergy of matter streams several authors have approached this task in several ways, including Fortran subroutines [3–5], compiled applications within the Aspen Plus® interface [6,7], or hand-made calculations.

The author's approach is the use of familiar software for the end user. Thus a VBA application was written in a Microsoft® Excel 2007 workbook, and the results and operations for the calculations are written in an Excel Workbook using Microsoft® Excel formulae, allowing the user to change whatever is needed to study a system with the aid of the exergetic cost, and the thermoeconomic cost data.

Once a process is simulated and run in the Aspen Plus® user interface, data from the matter, work and heat streams is collected and copy-pasted into the first three sheets of an Excel workbook. When the VBA application is executed (Fig. 1), the user is requested to provide this workbook. The application verifies that at least the first sheet (matter streams) has enough data to perform the calculations: mass flow, enthalpy, entropy. After verifying the data

Nomenclature

AER	Stable reference state at T_0, p_0, and reference substances from Szargut [1]
T_0	temperature of the AER [298.15 K]
p_0	pressure of the AER [121325 Pa]
h	specific enthalpy [kJ kg^{-1}]
h_0	specific enthalpy at T_0, p_0 [kJ kg^{-1}]
s	specific entropy [kJ kg^{-1} K^{-1}]
s_0	specific entropy at T_0, p_0 [kJ kg^{-1} K^{-1}]
b_{int}	specific internal exergy [kJ kg^{-1}]
b_{phys}	specific physical exergy [kJ kg^{-1}]
b_{chem}	specific chemical exergy [kJ kg^{-1}]
$\tilde{b}_{chem}$	specific chemical exergy [kJ mol^{-1}]
$\tilde{g}_{form}$	specific chemical exergy of formation [kJ mol^{-1}]
$\dot{B}_q$	Exergy of a heat flow [kW]
$\dot{Q}_q$	Heat flow [kW]
MHBT	Mass, energy, exergy, thermoeconomics
HHV	High heating value [kJ kg^{-1}]
ASU	Air separation unit
VBA	Microsoft® Visual Basic for Applications.
B^*	exergetic cost [kW]
A_{exs}	incidence cost matrix
A_{sxs}	cost matrix
$\alpha_{(s-e)xs}$	production matrix
Ω_{sx1}	allocated exergetic cost vector [kW]
$\omega_{(s-e)xs}$	assigned exergetic cost vector [kW]
B^*_{sx1}	exergetic cost vector [kW]
M_{sx1}	mass vector [kg/s]
H_{sx1}	energy vector [kg/s]
B_{sx1}	exergy vector [kW]
$B_{d,sx1}$	diagnostic vector
Φ_{sx1}	allocated thermoeconomic cost vector [\$ s^{-1}]
R	resource matrix
P	product matrix
I	looses matrix
Z	fixed cost of equipment [\$ s^{-1}]
Π_{sx1}	thermoeconomic cost vector [\$ s^{-1}]
Π	thermoeconomic cost [\$ s^{-1}]
O & M	Operation and maintenance
f	exergoeconomic factor
c	unit exergoeconomic cost [\$ MWh^{-1}]

Subscripts

d	destruction
r	resources
p	products
i	looses
s	stream
e	equipment
var	variable cost
tot	total cost
in	inputs

provided, the application starts with the calculations of matter, energy and exergy of all the streams (Section 2), creates a process structure matrix (Section 3), asks the user for the economic structure (Section 4) and other economic decisions about the streams (Section 5), the fixed cost of the equipment (Section 6) and the thermoeconomic costs of the resources (Section 7) to generate an Excel with the mass, energy, exergy, exergetic cost, thermoeconomic cost of all the streams, the mass, energy and exergy balances in each piece of equipment and several valuable indexes for evaluating the process (Section 8).

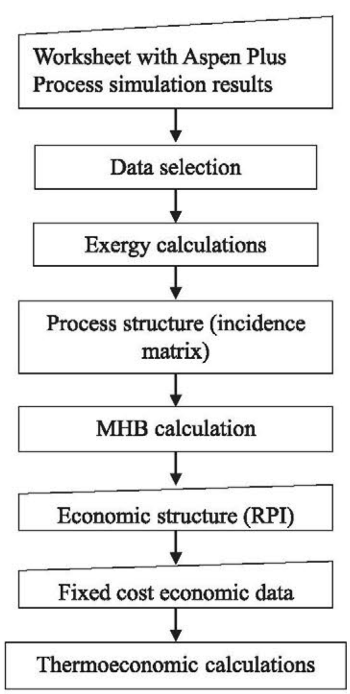

Fig. 1. Simplified algorithm of the MHBT VBA application.

An Air Separation Unit (ASU) is used as an example to run the application. The ASU presented in Fig. 2, is a cryogenic air distillation unit, based on the one presented by Amann et al. [8], but adapted to produce high purity oxygen (Table 1, stream 10503), as well as nitrogen for inerting purposes (stream 10403).

Because of the high rate of high purity oxygen flow needed, the technology selected for the ASU is a cryogenic distillation where air is slightly compressed (near 6 bar) and deeply cooled to temperatures within the liquid–vapour equilibrium (around −170 °C) in order to separate a highly purity nitrogen on top of a cryogenic distillation column provided with a total condenser (to control the N_2 purity) and an enriched oxygen flow on the bottom (no reboiler is used). The resulting streams enter in a lower pressure column with no condenser, but with a reboiler integrated with the condenser of the previous column (that's the reason why the low pressure column is built on top of the first column). The reboiler assures the required purity of the liquid oxygen obtained at the bottom of the low pressure column. The refrigeration needed for cooling is obtained with pressure drops and heat integration between the cold products and the incoming streams.

As shown in Fig. 2, the air stream 10101 is compressed in several stages (C101, C102) with intermediate cooling (E101, E102) making use of cooling water (CW, stream 11101). The compressed air 10105 is divided in two mass flows: 10106 and 10109. The first one (10106) is cooled in the main heat exchanger E201, and introduced in the high pressure column T201. The stream 10109 is further compressed (C103) and cooled (E103) before entering the main heat exchanger E201, being expanded (V201) to lower its temperature after it enters the high pressure column T201 of 36 theoretical stages [9] to obtain a rich nitrogen stream 10301 and an enriched oxygen stream 10201. The condenser of the high pressure column T201 is integrated with the reboiler from the low pressure column (T202), where the rich oxygen stream collected at the

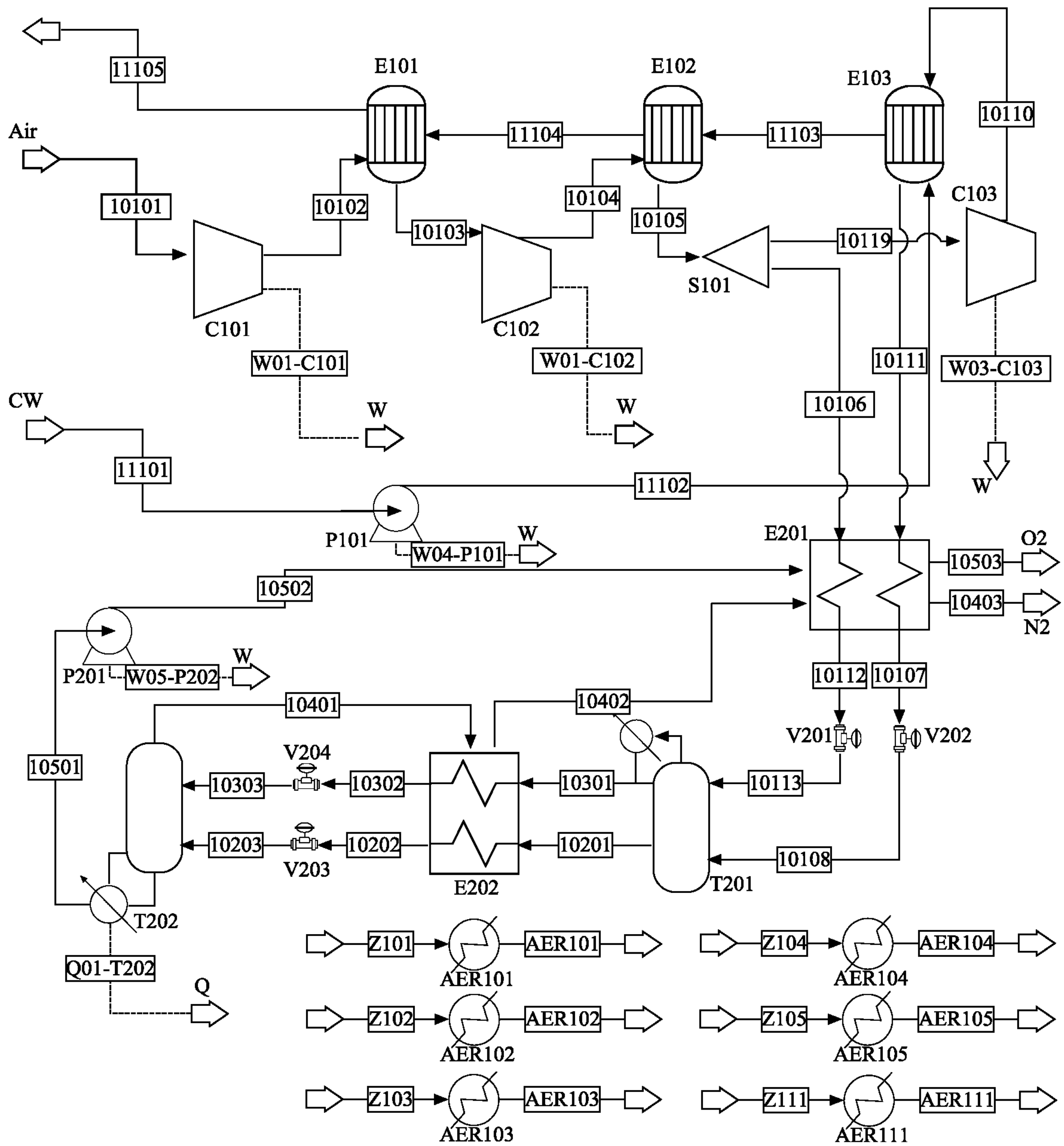

Fig. 2. Air separation unit (ASU) Aspen Plus® simulation.

bottom is partially reboiled making use of the heat (Q01-T202) taken from the high pressure column condenser, to ensure the correct composition of the rich oxygen stream product (10501), which is pumped in its liquid stage to the pressure needed. The rich nitrogen stream 10401 exiting the low pressure column is used in an intermediate exchanger (E202) to cool the exiting high pressure products before they are introduced in the low pressure and low temperature column T202 with 70 stages. Finally, the main exchanger E201, is used to warm the product streams 10402 (N_2) and 10502(O_2) and cool the incoming air streams 10106 and 10111.

2. Exergy calculations

Exergy calculations for matter streams can be divided into several terms, some of which have been disregarded in the calculations [6]: kinetic exergy (same as the kinetic energy value), potential exergy (same as the potential energy value). Nevertheless these terms can be added to the exergy values calculated, where only the internal exergy has been considered and calculated as the sum of the chemical and physical exergy:

$$b_{\text{int}} = b_{\text{chem}} + b_{\text{phys}} \tag{1}$$

2.1. Physical exergy of a matter stream

Physical exergy is calculated using Eq. (2) requiring information obtained in the Aspen Plus® simulation.

$$b_{\text{phys}} = h - h_0 - T_0(s - s_0) \tag{2}$$

The enthalpy and entropy data is automatically given by Aspen Plus® for each stream. Values of the same stream at AER temperature and pressure conditions can be also easily obtained using the following procedure:

a) Each matter stream is identified with 5 digits. The first 3 digits are the same for all the streams having the same composition.

Table 1
Data of the ASU streams.

Stream id	T [C]	P [bar,a]	M [kg/s]	Ar [% mole]	O_2 [% mole]	N_2 [% mole]	H_2O [% mole]
10101	25.00	1.01	100.00	0.010	0.210	0.780	0.000
10102	147.96	2.58	100.00	0.010	0.210	0.780	0.000
10103	30.00	2.58	100.00	0.010	0.210	0.780	0.000
10104	154.96	6.59	100.00	0.010	0.210	0.780	0.000
10105	30.00	6.59	100.00	0.010	0.210	0.780	0.000
10106	30.00	6.59	68.00	0.010	0.210	0.780	0.000
10107	−164.10	6.59	68.00	0.010	0.210	0.780	0.000
10108	−164.10	6.59	68.00	0.010	0.210	0.780	0.000
10109	30.00	6.59	32.00	0.010	0.210	0.780	0.000
10110	108.50	12.00	32.00	0.010	0.210	0.780	0.000
10111	24.65	12.00	32.00	0.010	0.210	0.780	0.000
10112	−164.10	12.00	32.00	0.010	0.210	0.780	0.000
10113	−173.10	6.59	32.00	0.010	0.210	0.780	0.000
10201	−172.11	6.59	61.76	0.013	0.316	0.672	0.000
10202	−180.60	6.59	61.76	0.013	0.316	0.672	0.000
10203	−192.42	1.06	61.76	0.013	0.316	0.672	0.000
10301	−178.39	5.07	38.24	0.006	0.046	0.948	0.000
10302	−184.00	5.07	38.24	0.006	0.046	0.948	0.000
10303	−194.63	1.06	38.24	0.006	0.046	0.948	0.000
10401	−194.46	1.06	78.21	0.012	0.016	0.972	0.000
10402	−175.00	1.06	78.21	0.012	0.016	0.972	0.000
10403	27.00	1.06	78.21	0.012	0.016	0.972	0.000
10501	−182.26	1.06	21.79	0.001	0.999	0.000	0.000
10502	−182.09	4.70	21.79	0.001	0.999	0.000	0.000
10503	27.00	4.70	21.79	0.001	0.999	0.000	0.000
11101	20.00	1.01	360.00	0.000	0.000	0.000	1.000
11102	20.00	3.00	360.00	0.000	0.000	0.000	1.000
11103	21.58	3.00	360.00	0.000	0.000	0.000	1.000
11104	28.89	3.00	360.00	0.000	0.000	0.000	1.000
11105	35.75	3.00	360.00	0.000	0.000	0.000	1.000
W01-C101			0.00	1.000	0.000	0.000	0.000
W02-C102			0.00	1.000	0.000	0.000	0.000
W03-C103			0.00	1.000	0.000	0.000	0.000
W04-P101			0.00	1.000	0.000	0.000	0.000
W05-P201			0.00	1.000	0.000	0.000	0.000
Q01-T202			0.00	1.000	0.000	0.000	0.000

b) A heat exchanger operating at AER temperature and pressure conditions is fed by a stream with exactly the same characteristics as the stream that is being evaluated making use of the Aspen Transfer utility. The stream exiting the heatX block will give the h_0, s_0, needed for all streams with same composition.

As the ASU has streams with 6 different compositions, 6 different AER heatX blocks have been considered as shown in Fig. 2.

Other authors [10,6] calculate the physical exergy of each pure substance present in the process. This methodology needs the calculation of a term called mixing exergy, related to the exergy destroyed when mixing pure components to reproduce the composition of the matter stream. This exergy destruction is associated to an entropy increase in the mixing process. With the procedure described in this paper, the physical exergy of each stream is calculated as a whole, avoiding the need of calculating the mixing exergy, as this term is already included in the physical exergy calculated, specifically in the entropy data of the streams, while other authors consider it part of the non-reactive chemical exergy [11].

The developed application has a module to find the information needed to perform calculations and a unit converter to read the following Aspen Plus® unit sets : SI, SICBAR, MET, METCBAR. Only the workbook data must be in one of these unit sets, which can be easily changed in the Aspen Plus® streams results view.

2.2. Chemical exergy of a matter stream

Chemical exergies are not included in the Aspen Plus® data base of pure substances, so it must be calculated by the user.

The MHBT application has a sheet named b_{chem} containing the chemical exergy and the HHV of several substances identified with the same name the user must use for the simulation in the Aspen Plus components name data. Every substance used in the simulation should have its corresponding values on this sheet, which can be actualised if necessary. The chemical exergy of any stream appearing in the Aspen Plus simulation that has all its substances in the b_{chem} sheet will be calculated using Eq. (3).

$$\tilde{b}_{\mathrm{chem}} = \sum_i x_i \cdot \tilde{b}_{\mathrm{chem},i} \tag{3}$$

For the values not present in the sheet, Excel is a very valuable help to calculate the exergy of pure substances using a table of chemical exergies [1] of elements and their free enthalpy of formation (or Gibbs function). Chemical exergy with these data can be evaluated using Eq. (4):

$$\tilde{b}_{\mathrm{chem}}(X) = \sum_i n_i \cdot \tilde{b}_{\mathrm{chem},i}(\mathrm{elems.}) + \tilde{g}_{\mathrm{form}}(X) \tag{4}$$

Once the chemical exergy of each element is calculated, the chemical exergy of each stream is calculated, but only once for each different stream composition as the specific chemical exergy (kJ/kg) is the same for all of them.

2.3. Work and heat streams exergy

Work is considered pure exergy, so the value given by Aspen Plus® is used directly as the exergy of each work stream, and its sign is used to identify if the work exits or enters the piece of equipment considering the Aspen Plus® sign criteria. The "+" sign is used when the work stream enters the piece of equipment (consumption), and the "−" sign is used when the work stream exits the piece of equipment (generation).

All the heat and work streams in the process shall be drawn in the Aspen Plus® simulation as outputs, to force their calculation by Aspen Plus, and show their values in the table of results. The exergy of a heat flow is given by Eq. (5):

$$\dot{B}_q = \left(1 - \frac{T_0}{T}\right) \cdot \dot{Q} \tag{5}$$

where heat $\dot{Q}$ and exergy $\dot{B}_q$ can have different signs. In this case the exergy sign will always be considered positive, considering its physical appropriate direction to make this happen.

Each heat and work stream should be named respectively with a Q and W letter, followed by two digits, a slash and the name of the piece of equipment from which it exits. This procedure is needed as Aspen Plus® does not give directly this information in the results view. Afterwards the user will be asked if he wishes to change the origin or end of any stream flow, allowing the user to make the necessary changes. In the ASU example, this is the case of the heat flow linking both columns: the oxygen reboiler of the upper low pressure column T202 receives heat from the nitrogen condenser of the lower high pressure column T201, although the heat is not linked in the simulation because the column block model does not allow the heat to enter the condenser. It must be noted that due to the cryogenic temperature at which oxygen boils when it is close to atmospheric pressure, the exergy of the heat flow and the energy heat flow have opposite directions, and therefore opposite signs when applying Eq. (5), prevailing the direction of the exergy flow (the one shown in Fig. 2 for Q01-T202), and therefore the heat has as a negative value (as it has the opposite direction).

3. Process structure and MHB calculation

Matter, energy and exergy balances are done with matrix calculations. The structure of the process is stored in an incidence matrix A_{exs} with one row per piece of equipment and one column per stream. The elements of this matrix will be 0 if the stream (column) has no relation with the piece of equipment (row), +1 if the stream is an input or −1 if the stream is an output.

The required information to build the incidence matrix is taken from the stream sheet of the workbook.

The same incidence matrix is used for the three balances, with the only need to change the vector to which it multiplies, which will contain the mass flowM_{sx1}, energy H_{sx1} and exergy B_{sx1} of each stream considered in the incidence matrix.

$$A_{exs}M_{sx1} = 0_{sx1} \tag{6}$$

$$A_{exs}H_{sx1} = 0_{sx1} \tag{7}$$

$$A_{exs}B_{sx1} = B_{d,sx1} \tag{8}$$

Eq. (6,7,8) show the mathematical formulation of the three balances *M*, *H*, *B*. The name MHBT given to the application is related to these three balances and the thermoeconomic (T) balance.

4. Economic structure

The user is asked about the economic structure (RPI classification) needed to calculate the exergetic cost of each stream [12,13]. The classification of each stream depends on the utility of the stream to the piece of equipment:

- Resources (*R*) will be the streams needed by the piece of equipment to fulfil its purpose. Other authors called them Fuel [10,13–15].
- The objectives of the piece of equipment will be classified as products (*P*) [15].
- Losses (*I*) will be any outputs of the process released to the environment with no further use or interest, but needed for technical reasons (heat, flue gases,...).

The *RPI* classification applied to the ASU is given in Table 2 and is stored in three different matrixes. Each matrix is stored in a different sheet, and has a similar structure to the incidence matrix, where a value of:

+1 corresponds to exiting products, incoming resources, and exiting losses (because these are the usual directions for them),
−1 corresponds to incoming products, exiting resources, and;
0 corresponds to all other cases, where the stream is not related to a piece of equipment and therefore is not a resource (*R* matrix), a product (*P* matrix) or a loss (*I* matrix).

RPI classification is usually a difficult task but this application makes it easier. If the end user wants to try several productive structures, results will be obtained quickly helping in the selection of the most appropriate *RPI* classification.

For consistency, the classification of a stream shall remain the same when considering the piece of equipment or the system as a whole. Thus the incoming flows to the system will surely be resources, and the exiting flows of the system most probably will be products or losses. In the ASU example this happens in the compressor C101, where the incoming air is not classified as a product as in C102, because it is an incoming resource to all the process.

Those pieces of equipment with the rare purpose of destroying exergy (condensers, radiators,...) are difficult to classify. This can be seen in E101, where all the streams are classified as resources, and the exiting air stream is the only product. Although at first sight, the air stream will be classified as a product, and the cooling water as a resource needed to decrease the temperature of the air, this classification is not advisable as the exergetic efficiency will be negative, because the product will have a negative value: the purpose of the piece of equipment is to reduce the temperature (and exergy) of the air stream. Thus, the purpose of E101 is the destruction of exergy (in agreement with [16]) for a technical reason: the temperature of the air exiting the first compressor shall be reduced before it enters the second compressor in order to increase the air density and reduce the compressor consumption.

Table 2
RPI initial guess.

Eq	Resources	Products	Looses
C101	10101; w01-c101	10102	
E101	10102; 11104	10103	11105
C102	w02-c102	10104; −10103	
E102	10104; 11103; −11104	10105	
S101	10105	10106; 10109	
E201	10106; 10111; 10402; 10502	10107; 10112; 10403; 10503	
V202	10107	10108	
C103	w03-c103	10110−10109	
E103	10110; 11102; −11103	10111	
V201	10112	10113	
T201	10108; 10113; q01-T202	10201; 10301	
E202	10401; −10402	10302; −10301; 10202; −10201	
V203	10202	10203	
V204	10302	10303	
T202	10203; 10303	10401; 10501; q01-T202	
P201	w05-p201	10502; −10501	
P101	11101; w04-p101	11102	

5. Exergetic costs

The exergetic cost of a stream is the quantity of exergy that has been consumed to produce the stream in the process. In a process with only one product the exergetic cost of the product is the exergy of all the resources consumed in the process, as for example the air and fuel consumed in a thermal power plant to produce electricity.

The use of exergy as a measurement unit for cost allocation [17] is also present in the exergetic cost balance of each piece of equipment where the cost of all the exiting streams equals the cost of all the incoming streams. As the number of exergetic costs (one per stream) to be calculated is higher than the number of cost balances (one per piece of equipment) [18], more equations are needed. The additional equations required can be obtained considering the productive structure given by the *RPI* classification (Section 4). The additional equations considered in the ASU are summarised in Table 3.

The application searches the additional equations as shown in Fig. 3, beginning with the easiest equations, and ending with the most difficult to find.

The easiest equations to find are the cost assigned to a stream classified as a lost, which is 0, in order to increase the costs of the rest of exiting streams (remember there is a balance cost in the piece of equipment, and the cost of the inputs is a fixed value), especially those classified as products. The possibility of using negative cost values for the losses [15], due to environmental requirements, is also considered in the application. The next easiest

Table 3
Additional equations ordered by equipment and type.

Eq	Resources	Unit costs	Looses
C101	10101; w01-c101		
E101			11105
C102	w02-c102		
E102		11103 = 11104	
S101		10106 = 10109	
E201		10107 = 10112; 10403 = 10112; 10403 = 10503	
V202			
C103	w03-c103		
E103		11102 = 11103	
V201			
T201		10201 = 10301	
E202		10401 = 10402; 10302 = 10202	
V203			
V204			
T202		10401 = 10501; 10401 = q01-T202	
P201	w05-p201		
P101	11101; w04-p101		

equations to find are those needed to evaluate the exergetic costs of the incoming resources, where usually the decision made is to assign them the exergy of the stream as their corresponding exergetic cost. Another possibility, also considered in the application, is to assign a cost equal to the exergy previously consumed to produce the stream considering the life cycle analysis of that resource, which is defined as the embodied exergy [19,20], as well as it is the basics for emergy analyses [21,22].

The next kind of equations to be considered is used to quantify the exergetic cost of the by-products. In this case the exergetic cost equals the exergy consumed to produce it using the best technology available in the market for that purpose.

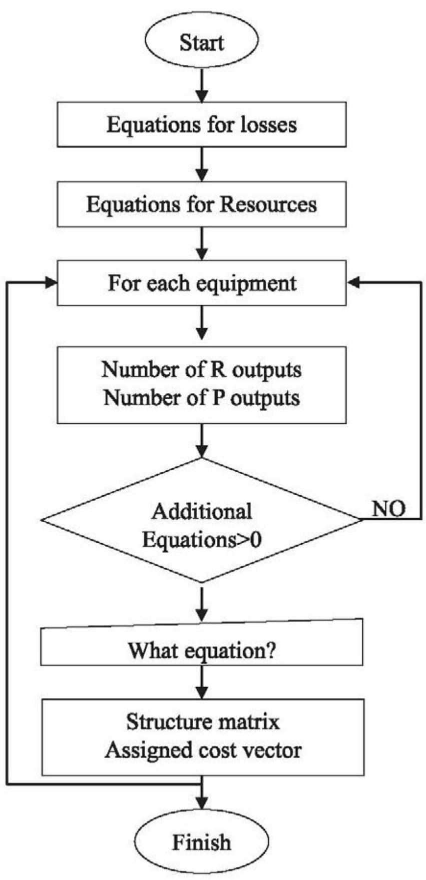

Fig. 3. Algorithm for additional equations.

The remaining equations are used to join the unit exergetic cost of:

- two exiting products (none is a by-product) of a piece of equipment (P-Principle [18]),
- an incoming resource with an exiting resource (F-Principle [18]).

Considering s streams and e pieces of equipment the number of additional equations needed is (s-e), allowing the exergetic cost calculation by using Eq. (9) :

$$A_{sxs}B^{*}_{sx1} = \Omega_{sx1} \tag{9}$$

The following procedure has been followed to find how to ask the user about the additional equations in the order shown in the algorithm of Fig. 3 :

1) For each piece of equipment the exergetic cost of the incoming streams has been decided previously, or they are incoming resources to the whole system (air from the environment, power consumed in the compressors, ...). In both cases only the exit streams shall be considered in order to find if additional equations should be added to solve the system. If only one stream exits the piece of equipment the exergetic cost balance equation is enough to calculate the costs, and no additional equations are required.
2) If more than one stream exits the piece of equipment then additional equations should be considered [15]. Particularly (N_s−1) equations are needed (N_s = number of exiting streams) as one equation will be the exergetic cost balance, or the thermoeconomic cost balance. The possible additional equations are:
   a) If one of the exiting streams is a loss then an additional equation is to assign that stream an exergetic/thermoeconomical cost of 0.
   b) If one of the exiting streams is a by-product, then its cost is given by the minimum unit exergetic/exergoeconomic cost of production of that product considering the best available technology.
   c) If one of the exiting streams is a resource, then the unit exergetic/exergoeconomic cost of the exiting resource equals the unit cost of an input resource.
   d) If products of the same importance exit the piece of equipment, then the appropriate equation is to give them the same unit exergetic/exergoeconomic cost.

The user is asked about which of these options should be considered for the additional equations needed.

The economic structure matrix is added below the incidence matrix [12], to build the cost matrix A_{sxs} that contains Eq. (10). The allocated exergetic cost vector Ω_{sx1} has zeros in the first e elements (equations of exergetic cost balances) followed by the appropriate terms corresponding to the additional equations considered, in the same order that they have been considered in the economic structure matrix shown in Fig. 4. Table 3 shows the equations that have been added to solve the system for the ASU case.

6. Fixed cost economic data

The user is asked about the fixed cost data (Z) assigned to each piece of equipment in the process [23]. These calculations can be performed with the aid of ASPEN, by hand using known procedures

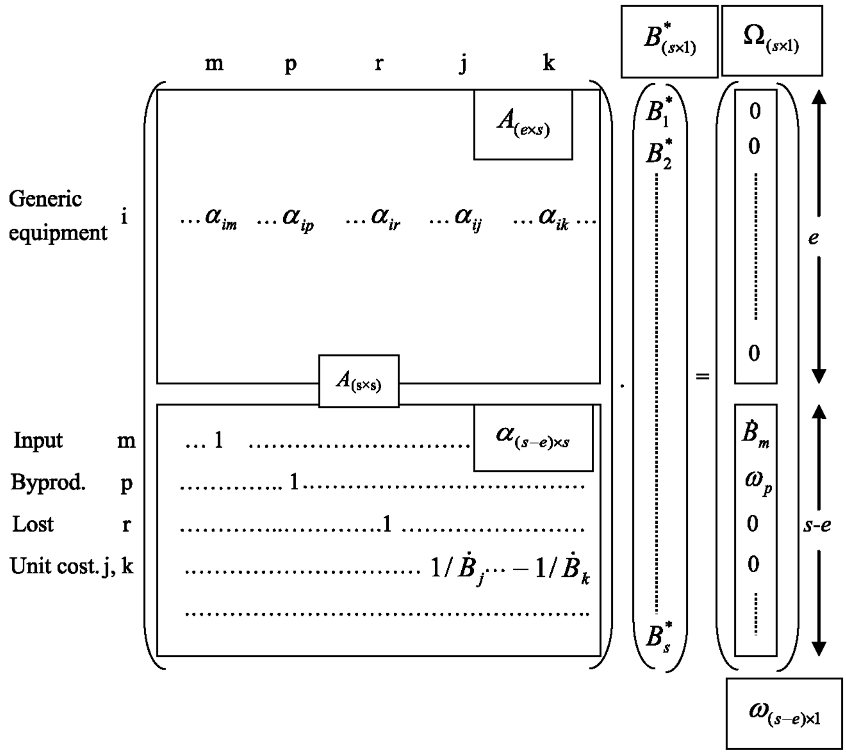

Fig. 4. Exergetic cost matrix.

such us the ones described on [24], or with the aid of the method shown in the Baasel book [25]. The application allow the user to choose the option preferred, and offers a confortable way of using the tables present of the Baasel book [25], which are included in the application in several sheets and that can be easily changed by the user. The user can also choose to calculate the variable thermoeconomic costs.

As the decisions made are included in the final workbook as well as all the calculations, it is really easy to study the system varying the fixed cost assigned to the equipment to perform a sensibility analysis or to analyse different budget or purchasing possibilities.

This has been done with the ASU, where total costs and variable costs have been calculated. The total fixed cost of the equipment has been determined considering a total investment cost for the ASU of 1376 k\$ (kg/s O_2)$^{-1}$ [26], 8000 h/year of annual operation hours, a plant life of 20 years, and annual interest rate of 4%, no loan made for the total plant investment (TPI), and an annual O&M factor of 5% of the TPI. This total fixed cost has been distributed to the pieces of equipment present on the ASU by the ratio between the installed costs (IEC) of each piece of equipment and the total installed cost of the equipment. These values are not shown in Tables 4 and 5 as in variable cost calculations $Z = 0$ for the equipment. In Table 6, the values for the fixed costs used to calculate the thermoeconomic costs for the ASU are shown in column Z.

7. Thermoeconomic costs

After the previous decision has been made, the only additional information required is the exergoeconomic unit cost of the incoming resources of the whole system.

Table 4
Exergy results for the ASU equipment.

Eq	B_d [kW]	d_r	B_r [kW]	B_p [kW]	B_i [kW]	E_{ff}	B_d/Br	B_{in} [kW]	Loss coef.	Signif. Factor	Loss comp.
C101	2375	0.10	17620	15245	0	0.87	0.13	17620	0.1	12809	1727
E101	1799	0.07	77734	13221	62714	0.17	0.02	77734	0.8	62649	51994
C102	2377	0.10	12625	10249	0	0.81	0.19	25847	0.1	62906	5784
E102	1988	0.08	23213	21225	0	0.91	0.09	85703	0.0	268722	6234
S101	0	0.00	21225	21225	0	1.00	0.00	21225	0.0	71772	0
E201	1434	0.06	52878	51444	0	0.97	0.03	52878	0.0	178807	4850
V202	0	0.00	22516	22516	0	1.00	0.00	22516	0.0	83827	0
C103	571	0.02	2534	1963	0	0.77	0.23	9326	0.1	34719	2124
E103	590	0.02	9021	8432	0	0.93	0.07	71254	0.0	343528	2843
V201	179	0.01	20796	20617	0	0.99	0.01	20796	0.0	104425	897
T201	4454	0.18	43133	38679	0	0.90	0.10	74335	0.1	390093	23376
E202	416	0.02	3854	3438	0	0.89	0.11	87247	0.0	667869	3188
V203	510	0.02	45178	44668	0	0.99	0.01	45178	0.0	358949	4053
V204	277	0.01	28141	27864	0	0.99	0.01	28141	0.0	245622	2417
T202	7460	0.30	72532	65071	0	0.90	0.10	72532	0.1	692576	71237
P201	12	0.00	10	−1	0	−0.12	1.12	16514	0.0	8832030	6276
P101	73	0.00	62571	62499	0	1.00	0.00	62571	0.0	53983192	62571

Table 5
Thermoeconomic results for the ASU equipment (Variable cost).

Eq.	Π_r [\$/s]	Π_p [\$/s]	c_r [\$/MWh]	c_p [\$/MWh]	$c_r \cdot B_p$ [\$/s]	$c_r \cdot B_i$ [\$/s]	$c_r \cdot B_d$ [\$/s]	$(c_p - c_r) \cdot B_p$ [\$/s]	$(c_p - c_r)/c_r$
C101	0.21	0.21	43.08	49.79	0.18	0.00	0.0284	0.0284	0.1558
E101	0.21	0.21	9.83	57.80	0.04	0.17	0.0049	0.1762	4.8796
C102	0.21	0.21	61.17	75.35	0.17	0.00	0.0404	0.0404	0.2319
E102	0.43	0.43	66.19	72.39	0.39	0.00	0.0366	0.0366	0.0937
S101	0.43	0.43	72.39	72.39	0.43	0.00	0.0000	0.0000	0.0000
E201	2.97	2.97	202.44	208.08	2.89	0.00	0.0807	0.0807	0.0279
V202	1.30	1.30	208.08	208.08	1.30	0.00	0.0000	0.0000	0.0000
C103	0.04	0.04	61.17	78.95	0.03	0.00	0.0097	0.0097	0.2906
E103	0.18	0.18	71.69	76.70	0.17	0.00	0.0117	0.0117	0.0699
V201	1.20	1.20	208.08	209.88	1.19	0.00	0.0103	0.0103	0.0087
T201	2.50	2.50	208.94	233.01	2.24	0.00	0.2585	0.2585	0.1152
E202	0.32	0.32	300.26	336.63	0.29	0.00	0.0347	0.0347	0.1211
V203	3.34	3.34	266.49	269.53	3.31	0.00	0.0378	0.0378	0.0114
V204	2.08	2.08	266.49	269.14	2.06	0.00	0.0205	0.0205	0.0099
T202	5.43	5.43	269.38	300.26	4.87	0.00	0.5582	0.5582	0.1147
P201	0.00	0.00	61.17	−517.13	0.00	0.00	0.0002	0.0002	−9.4540
P101	0.00	0.00	0.08	0.08	0.00	0.00	0.0000	0.0000	0.0012

$$A_{sxs}\Pi_{sx1} + \Phi_{sx1} = 0_{sx1} \quad (10)$$

In this case the Φ_{sx1} vector (allocated thermoeconomic costs vector) has the fixed cost values (Z) of the equipment as the first e elements, and the values of the additional equations that have been considered are all 0 except for the incoming resources and by-products where the value of their thermoeconomic costs must be provided by the user. For the ASU example it has been decided to assign no cost for air and cooling water, as their costs are negligible compared to the cost considered for the power consumed: 61.17/MWh [27].

8. Indexes and evaluation

Several indexes are calculated by the application, as shown in Table 4, Table 5, and Table 6, that allow the user to study the system from an exergetic and a thermoeconomic point of view.

The following exergy indexes are calculated for each piece of equipment (Table 4):

1) B_d: Exergy destruction.
2) d_r: Relative exergy destruction. Not only B$_d$ is important, but also the ratio between the destruction in the equipment regarding and to the exergy destroyed in the whole system.
3) B_r: Exergy of the resources.
4) B_p: Exergy of the products.
5) B_i: Exergy of the losses.
6) E_{ff}: Exergetic efficiency [2], which is B_r/B_p.
7) B_d/B_r: Exergy destruction ratio [2], exergy destroyed in the piece of equipment compared to the exergy of the resources consumed.
8) $(B_d + B_i)/B_{in}$: Loss coefficient [28].
9) Significance factor [28].
10) Loss component [28].

For the pieces of equipment the following thermoeconomic indexes are calculated, as shown respectively on Table 5 and Table 6 for the ASU:

1) Π_r: Thermoeconomic cost of the resources.
2) Π_p: Thermoeconomic cost of the products.
3) c_r: Unit exergoeconomic cost of the resources.
4) c_p: Unit exergoeconomic cost of the products.
5) $c_r \cdot B_p$: Thermoeconomic cost of the products if the exergy destruction, losses, and fixed cost are 0.
6) $c_r \cdot B_i$:Thermoeconomic cost of the exergy losses [2,29,30].
7) $c_r \cdot B_d$: Thermoeconomic cost of the exergy destruction [2].
8) $(c_p - c_r) \cdot B_p$: Absolute overcost, which gives information of the difference between $c_r \cdot B_p$ and the thermoeconomic cost of the product because of the exergy losses and destruction, and the fixed costs of the equipment.
9) $(c_p - c_r)/c_r$: Relative overcost or relative cost difference [2]. Gives information about how much the unit exergoeconomic

Table 6
Thermoeconomic results for the ASU equipment (Total cost).

Eq.	Z [\$/s]	Π_r [\$/s]	Π_p [\$/s]	c_r [\$/MWh]	c_p [\$/MWh]	$c_r \cdot B_p$ [\$/s]	$c_r \cdot B_i$ [\$/s]	$c_r \cdot B_d$ [\$/s]	$(c_p - c_r) \cdot B_p$ [\$/s]	$(c_p - c_r)/c_r$	f
C101	0.052	0.21	0.26	43.08	62.01	0.18	0.00	0.0284	0.0801	0.4393	0.39
E101	0.004	0.26	0.27	12.26	73.15	0.05	0.21	0.0061	0.2236	4.9685	0.02
C102	0.052	0.21	0.27	61.17	93.78	0.17	0.00	0.0404	0.0928	0.5331	0.36
E102	0.003	0.54	0.54	83.07	91.34	0.49	0.00	0.0459	0.0488	0.0995	0.06
S101	0.000	0.54	0.54	91.34	91.34	0.54	0.00	0.0000	0.0000	0.0000	0.00
E201	0.000	3.79	3.79	257.85	265.04	3.68	0.00	0.1027	0.1027	0.0279	0.00
V202	0.000	1.66	1.66	265.04	265.04	1.66	0.00	0.0000	0.0000	0.0000	0.00
C103	0.014	0.04	0.06	61.17	104.72	0.03	0.00	0.0097	0.0238	0.7120	0.37
E103	0.001	0.23	0.23	91.56	98.58	0.21	0.00	0.0150	0.0164	0.0766	0.08
V201	0.000	1.53	1.53	265.04	267.33	1.52	0.00	0.0131	0.0131	0.0087	0.00
T201	0.000	3.19	3.19	266.13	296.82	2.86	0.00	0.3293	0.3297	0.1153	0.00
E202	0.000	0.41	0.41	382.60	428.94	0.37	0.00	0.0443	0.0443	0.1211	0.00
V203	0.000	4.26	4.26	339.52	343.40	4.21	0.00	0.0481	0.0481	0.0114	0.00
V204	0.000	2.65	2.65	339.52	342.90	2.63	0.00	0.0261	0.0261	0.0099	0.00
T202	0.001	6.91	6.92	343.21	382.60	6.20	0.00	0.7112	0.7121	0.1148	0.00
P201	0.000	0.00	0.00	61.17	−1108.83	0.00	0.00	0.0002	0.0004	−19.1270	0.34
P101	0.001	0.00	0.00	0.08	0.12	0.00	0.00	0.0000	0.0007	0.4673	0.50

Table 7
Results for the ASU streams (variable and total costs).

Stream	B [kW]	B^* [kW]	B^*/B	Π_{var} [$/s]	Π_{tot} [$/s]	Π_{var}/B [$/MWh]	Π_{tot}/B [$/MWh]	Π_{var}/B^* [$/MWh]	Π_{tot}/B^* [$/MWh]
10101	5210	5210	1.00	0.00	0.00	0.00	0.00	0.00	0.00
10102	15245	17620	1.16	0.21	0.26	49.79	62.01	43.08	53.65
10103	13221	80182	6.06	0.21	0.27	57.80	73.15	9.53	12.06
10104	23470	92807	3.95	0.43	0.54	65.47	82.16	16.56	20.78
10105	21225	92550	4.36	0.43	0.54	72.39	91.34	16.60	20.95
10106	14433	62934	4.36	0.29	0.37	72.39	91.34	16.60	20.95
10107	22516	264040	11.73	1.30	1.66	208.08	265.04	17.74	22.60
10108	22516	264040	11.73	1.30	1.66	208.08	265.04	17.74	22.60
10109	6792	29616	4.36	0.14	0.17	72.39	91.34	16.60	20.95
10110	8755	32150	3.67	0.18	0.23	73.86	94.34	20.11	25.69
10111	8432	32416	3.84	0.18	0.23	76.70	98.58	19.95	25.64
10112	20796	243862	11.73	1.20	1.53	208.08	265.04	17.74	22.60
10113	20617	243862	11.83	1.20	1.53	209.88	267.33	17.74	22.60
10201	42831	634917	14.82	3.13	3.99	263.04	335.12	17.74	22.61
10202	45178	678492	15.02	3.34	4.26	266.49	339.52	17.74	22.61
10203	44668	678492	15.19	3.34	4.26	269.53	343.40	17.74	22.61
10301	27050	400975	14.82	1.98	2.52	263.04	335.12	17.74	22.61
10302	28141	422624	15.02	2.08	2.65	266.49	339.52	17.74	22.61
10303	27864	422624	15.17	2.08	2.65	269.14	342.90	17.74	22.61
10401	17366	293865	16.92	1.45	1.85	300.26	382.60	17.74	22.61
10402	13512	228641	16.92	1.13	1.44	300.26	382.60	17.74	22.61
10403	2837	33264	11.73	0.16	0.21	208.08	265.04	17.74	22.60
10501	16503	279261	16.92	1.38	1.75	300.26	382.60	17.74	22.61
10502	16502	279271	16.92	1.38	1.75	300.33	382.71	17.75	22.61
10503	5295	62097	11.73	0.31	0.39	208.08	265.04	17.74	22.60
11101	62488	62488	1.00	0.00	0.00	0.00	0.00	0.00	0.00
11102	62499	62571	1.00	0.00	0.00	0.08	0.12	0.08	0.12
11103	62233	62305	1.00	0.00	0.00	0.08	0.12	0.08	0.12
11104	62490	62562	1.00	0.00	0.00	0.08	0.12	0.08	0.12
11105	62714	0	0.00	0.00	0.00	0.00	0.00	1.00	1.00
W01-C101	12409	12409	1.00	0.21	0.21	61.17	61.17	61.17	61.17
W02-C102	12625	12625	1.00	0.21	0.21	61.17	61.17	61.17	61.17
W03-C103	2534	2534	1.00	0.04	0.04	61.17	61.17	61.17	61.17
W04-P101	83	83	1.00	0.00	0.00	61.17	61.17	61.17	61.17
W05-P201	10	10	1.00	0.00	0.00	61.17	61.17	61.17	61.17
Q01-T202	31202	527990	16.92	2.60	3.32	300.26	382.60	17.74	22.61

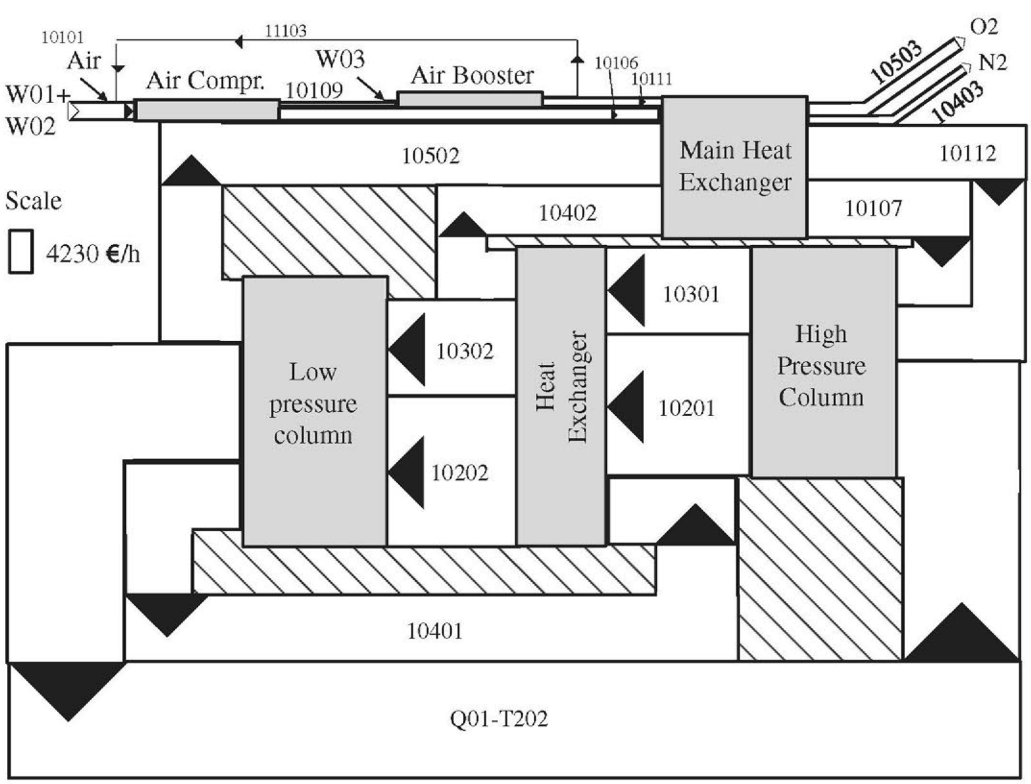

Fig. 5. Thermoeconomic cost representation.

cost of the product increases compared to the incoming resource unit cost in each piece of equipment.

10) "f" or Exergoeconomic factor [2]: ratio between the cost of the equipment (Z) and the sum of the following terms: of the cost of the equipment Z, the cost of the exergy losses $c_r \cdot B_i$, and the cost of the exergy destruction $c_r \cdot B_d$.

Table 5 and Table 6 show the little influence of the fixed cost of the piece of equipment Z on the total costs of the resource Π_r and the productΠ_p . Also the exergoeconomic factor f have values below 0.5 because the variable costs are far more important than the fixed costs.

It can be observed that the c_p of the pump P201 has a negative sign, due to the decrease in exergy in the fluid being pumped, as the pressure increment has low significance in the exergy compared to the lightly increase in the low temperature of the original stream.

For the streams the following indexes are calculated (Table 7):

1) B^*/B: Unit exergy cost [31]. Exergetic cost divided by the exergy of the stream.
2) Π/B: Unit exergoeconomic cost of the stream.
3) Π/B^*: Unit thermoeconomic cost of the stream.

where in the case of the ASU the values are given in Table 7 for variable and total cost analyses. These values have little differences in the two cases in agreement with the exergy results.

With this information the user will be able to evaluate a project design according to the following rules:

1) Rank the pieces of equipment in descending order of absolute cost differences.
2) Start studying design improvements for those pieces of equipment with higher absolute cost differences
3) Pieces of equipment with high relative costs differences must be considered very carefully.
4) Make choices based on the value of the exergoeconomic factor:
   a) If this factor is high, an investment reduction should be considered, even though thermodynamic efficiency could be impaired.
   b) If it is low, a thermodynamic efficiency increase should be tried with a better (and more expensive) piece of equipment.
5) Explore thermodynamic improvements of any piece of equipment with low exergetic efficiency or high exergy destruction (both absolute and relative), or high exergy loss ratio. The identification of the endogenous and exogenous terms of exergy destruction can contribute to a better understanding of the process, in an advanced exergy analysis [32,33]. This procedure has been considered of interest for cryogenic processes [34].

9. Conclusions/discussion

A tool in VBA for Microsoft® Excel 2007 has been developed for the project engineer that can be used as a complement to Aspen Plus®.

An Excel worksheet with all the operations and calculations is obtained, that can be modified to study different alternatives of the same process. The operations track can also be followed in the well-known Excel interface. This application should not be used in previous Excel versions as the matrix formulae have a limit in the size of the matrixes they can handle. In Microsoft® Excel 2007 there is no limitation.

All the calculations done in the resulting workbook depends on the Aspen Plus® data and the decisions taken by the user. Therefore changes on the Aspen Plus® data sheets will be reflected in the solutions directly, making really easy the study of different scenarios for the same process, as for example: different efficiencies for a piece of equipment, different costs for a piece of equipment, different costs for the incoming resources.

These possibilities make the results workbook a valuable tool to perform sensibility analysis.

This application is open to anyone interested in it, without any other restriction than giving the reference of this paper when using the application or modifying the code.

The application user interface allows the translation to any other language than Spanish and English just by adding a new column in the "Lang" sheet of the application.

The application was used to study an air separation unit, as well as the influence of variable and total costs in the operation. The results of the exergy and thermoeconomic costs have been presented in a graphical way (Fig. 5 already presented in [35] showing that the fixed costs are so low in the total costs of the products that a continuous up-to-date of the process should be considered during the life of the plant and even a complete renovation of the plant can be advisable. The graphical representation of the thermoeconomic results is a convenient way to show the results as it can be used to verify: that the cost of the exits is higher than the cost of the inputs, the influence of fixed costs over variable costs, where the products increase highly or slightly their costs in each piece of equipment. This is shown in Fig. 5 for the ASU, where this highly integrated process, gives a product with a thermoeconomic cost (0.60 euro/s) close to the cost of the power consumed (0.47 euro/s).

Appendix A. Check if you can use this application with your Aspen Plus® simulation

The same name must be used for the components in the Aspen Plus® interface and the b_{chem} sheet in the MHBT workbook.

All the streams are named with 5 digits. The first 3 are equal for all the streams with same composition.

For each different composition (identified by the 3 digits) a heatX, named AER followed by 3 digits, working at the reference state conditions must be used.

The output stream of the heatX is named AER followed by the 3 digits, and its h, and s, will be the h_0, s_0 needed to calculate the physical exergy of all the streams with that composition (beginning their names with the 3 aforementioned digits).

The input stream for the heatX AER is named z followed by the 3 digits. Aspen Plus® transfer function may be used to give this stream the exact composition of any of the streams defined by those 3 digits.

The pieces of equipment will be named with a letter followed by 3 digits. It is recommended to use a letter related to the function of the piece of equipment, except for letter z : E for exchangers, T for turbines, P for pumps, ...

If the first letter of the piece of equipment is z it will not be considered in the analysis. If this is the case the user will be asked to relocate the new origin or target of the streams affected by this piece of equipment. This is useful in those cases where several Aspen Blocks (for example a fuel cell) are used to represent only one piece of equipment, i.e. a fuel cell.

If the name of a stream is preceded by z that stream will not be considered. This can be used for auxiliary streams not corresponding to real ones, i.e. an auxiliary heat stream connecting two Aspen Plus® blocks used to simulate one piece of equipment.

Every work stream that must be considered should be included explicitly in the Aspen Plus® Flowsheet as an exiting work, by doing this, all work streams in the process will be available to copy-paste them from the Aspen Plus Results user interface.

Every work stream must be named as W followed by 2 digits a dash and the name of the piece of equipment. i.e. W01-P302 is a work of the piece of equipment named P302, which is a pump (P).

Every heat stream considered must be included explicitly in the Aspen Plus® Flowsheet.

Every heat stream should be named with a Q followed by 2 digits a dash and the name of the piece of equipment, i.e. Q03-H401 is a heat of the piece of equipment named H401, which is a Heat exchanger (H).

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